Recommendations for Stormwater Management in the Plum Creek Watershed

By
Stephen Eddy Fuhrer II
Department of Environmental Science
Allegheny College
Meadville, Pennsylvania

April, 2014

Recommendations for Stormwater Management in the Plum Creek Watershed

By
Stephen Eddy Fuhrer II
Department of Environmental Science
Allegheny College
Meadville, Pennsylvania

April, 2014

Submitted in fulfillment of the senior thesis requirements of the
Department of Environmental Science at Allegheny College
and approved by the senior thesis committee.

_____	_____	_____	_____
Dr. Kate Darby	Date	Mr. Christopher Shaffer	Date

_____

Pledge

Table of Contents

ABSTRACT 5
INTRODUCTION 6
Urban Hydrology 6
Water Contamination 8
Flood Risks 9
Management Techniques 9
Porous Pavement 10
Detention/Retention Basins 11
Green Roofs 12
Other Techniques 13
Pittsburgh Stormwater 15
METHODS 17
Study Site 17
GIS Data Collection 19
Suitability Analysis 19
Porous Pavement 20
Stormwater Basins 21
Green Roofs 22
Rain Gardens 22
Riparian Buffer Health 23
RESULTS 24
Porous Pavement 24
Stormwater Basin 25
Green Roofs 26
Rain Gardens 27
Riparian Zone Health 28
RECOMMENDATIONS 29
Residential Plan 29

Commercial Plan 31
Intensive Plan 32
Riparian Zone Remediation Plan 34
Limitations 36
Conclusion 37
APPENDIX: SITE OVERVIEWS 38
ACKNOWLEDGEMENTS 41
REFERENCES 42

List of Figures

Figure 1: The Water Cycle 7
Figure 2: Retention Basin 11
Figure 3: Allegheny County 16
Figure 4: Plum Creek Watershed 2006 Land Cover 17
Figure 5: Plum Creek Watershed 1992 Land Cover 18
Figure 6: Porous Pavement Suitability 24
Figure 7: Stormwater Basin Suitability 25
Figure 8: Green Roof Suitability 26
Figure 9: Rain Garden Suitability 27
Figure 10: Riparian Health Suitability 28
Figure 11: Plan #1 Site A 30
Figure 12: Plan #1 Site B 31
Figure 13: Plan #2 Site A 32
Figure 14: Plan #3 Site A 33
Figure 15: Plan #3 Site B 34
Figure 16: Plan #4 Example 1 35
Figure 17: Plan #4 Example 2 36
Appendix Figure 1: Residential Plan Site A Overview 38
Appendix Figure 2: Residential Plan Site B Overview 38
Appendix Figure 3: Commercial Plan Site A Overview 39
Appendix Figure 4: Intensive Plan Site A Overview 39
Appendix Figure 5: Intensive Plan Site B Overview 40
Appendix Figure 6: Riparian Zone Site A Overview 40

List of Tables

Table 1: Data Layers and Sources 19
Table 2: Porous Pavement Soil Drainage 20
Table 3: Porous Pavement Slope 20
Table 4: Stormwater Basin Slope 21
Table 5: Stormwater Basin Land Cover 21
Table 6: Green Roof Size 22
Table 7: Rain Garden Slope 22
Table 8: Rain Garden Land Cover 23
Table 9: Riparian Zone Health 23

Name: Stephen Eddy Fuhrer II Date: Spring, 2014
Major: Environmental Science
Thesis Committee: Dr. Kate Darby, Mr. Christopher Shaffer

Title: **Recommendations for Stormwater Management in the Plum Creek Watershed**

Damage from poor stormwater management has plagued the city of Pittsburgh for years. Stormwater runoff can lead to flash flooding and severe water contamination, both of which are damaging to property and the environment, and in some cases, result in loss of life. This research looks to find the optimal locations for the employment of stormwater mitigation techniques in the Plum Creek Watershed. Some of the best management practices for stormwater include utilizing porous pavements, stormwater basins, and green roofs. The study site was examined using a GIS analysis that ranks the suitability for different management types. The resulting suitability maps were used to make recommendations for stormwater management within the Plum Creek Watershed. Managing watersheds upstream of at-risk areas is important because of the direct effect that it can have on the overall water levels and water quality downstream.

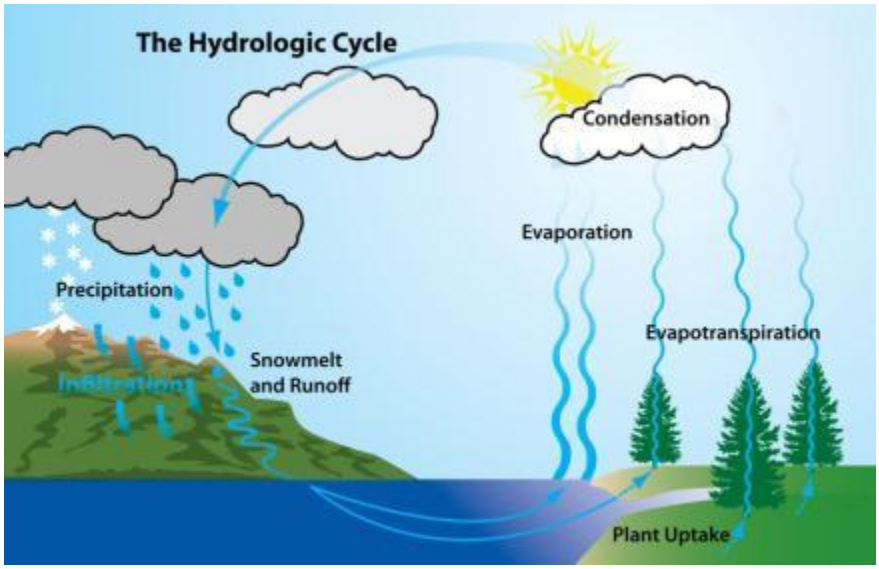
Introduction

Urban Hydrology

Urbanization is a significant issue that is a source of many environmental woes in the world today. For most of history, the majority of people lived in a rural setting, but this trend started to shift at the beginning of the 20th century (Bilsborrow, 1998). Starting with the industrial revolution and the mass production of automobiles, cities began developing impervious roads to facilitate travel (Lazaro, 1990). Cities started to grow due to an influx of immigrants and permanent structures were built to accommodate the growing population (Bilsborrow, 1998). Eventually, urban areas became the central hub for their surroundings because of the special services and functions that they performed (Lazaro, 1990). Once the automobile was invented, people no longer were forced to live in proximity to their workplace (Lazaro, 1990). Massive road networks were created so that travel to and from the city and suburbs was simple (Lazaro, 1990). This rapid growth would have permanent effects on the natural environment in a variety of ways. One of the most devastating outcomes of urbanization on the natural environment is the effects that it has had on hydrology.

The hydrologic cycle is made up of physical processes that govern the movement of water (Figure 1). Water evaporates from the oceans and other surface waters and the vapor travels into the atmosphere where it condenses. This condensation causes precipitation to fall to the surface where either it infiltrates the soil or it becomes surface runoff. Surface runoff follows the topography of the land until it empties into surface water features, which eventually evaporate and the process begins again. Precipitation that infiltrates the soil either percolates into groundwater or is absorbed by plant roots and then transpired back into the atmosphere. Groundwater eventually moves into the ocean or other large surface water features.

Figure 1: The Water Cycle (http://www.state.nj.us/drbc/hydrological/)



Anthropogenic structures disrupt the infiltration process in the cycle, causing excess surface runoff and decreased groundwater repletion (Lazaro, 1990). To keep inhabitants safe from flooding, streets were designed to avert any water that stemmed from a storm event into a sewer system or a nearby waterway (Arnold & Gibbons, 1996). While this concept might have worked initially, the extensive construction of impervious surfaces was too much for the storm drains and rivers to handle which resulted in downstream flooding and sewer overflow during heavy rainfall (Arnold & Gibbons, 1996). Eventually, scientists discovered that impervious surfaces were not only an aggravator of flooding, but also carried the potential for water contamination.

Roads and parking lots made of asphalt or concrete are two of the best examples of impervious surfaces in urban areas. The construction of new buildings is almost always coupled with the creation of parking lots or even new roads, which are known to be extremely harmful sources of runoff pollution. Roofs are also considered impervious surfaces and have been known to carry toxins, either from the precipitation or from the protective layer deteriorating (Arnold & Gibbons, 1996). Many city planners and ecologists use the amount of impervious surfaces in an area to grade the overall health of nearby watersheds (Arnold & Gibbons, 1996). Once an area reaches 10% impervious coverage nearby watersheds are likely impacted and when impervious cover reaches 30%, the stream health is degraded (Arnold & Gibbons, 1996). The amount of

runoff produced, evaporation frequency, and infiltration levels can also be estimated based on the percentage of imperviousness in an area (Environmental Protection, 1993). For example, an area covered by 75% impervious surface creates 45% more runoff and allows for 35% less ground infiltration compared to natural ground cover (Environmental Protection, 1993). Most urban areas have anywhere from 30 to greater than 50% impervious cover (Dengsheng & Qihao, 2006).

Water Contamination

Urban runoff pollution occurs because the chemicals that are often found in urban places are picked up by flowing water that happens during rainfall and then carried into surface waters or sewer systems (Newkirk, 2000). The most prevalent pollutants found in stormwater are suspended solids, nitrogen, phosphorus, lead, iron, and bacteria such as *E.coli* (Lee & Bang, 2000). Suspended solids cause turbidity in water and smother the aquatic life (Tsihrintzis & Hamid, 1997). Heavy metals have been known to bioaccumulate throughout the food chain and eventually find their way into humans (Tsihrintzis & Hamid, 1997). Highways are an especially significant source of runoff pollution because of the suspended solids, heavy metals, and hydrocarbons released from traffic that are swept away during runoff (Pagotto et al, 2000). Automobiles are a primary source of many of the pollutants found in stormwater (Pitt et al, 1995). Cars contribute much of the toxic nature to stormwater whenever runoff picks up traces of spilled gasoline, oil, tire residue, and exhaust particles (Pitt et al, 1995). In addition, newer surfaces are more prone to chemical buildup and runoff than older surfaces because of the lack of cracks and deterioration that eventually take place over time (Brattebo & Booth, 2003). To put the toxicity of stormwater into perspective, a study from Bryan (1972) concluded that urban stormwater often has comparable contamination to raw sanitary sewage. The pollution of urban watersheds also has the potential for serious health effects (Gaffield et al, 2003). When chemicals are combined through runoff, some can react synergistically and produce harmful effects greater than the sum of their individual parts (Gaffield et al, 2003). There is evidence that runoff from poor stormwater management can carry carcinogens and harmful bacteria that affect humans and animals when ingested (Gaffield et al, 2003). Along with the problems associated with urban runoff contamination, impervious surfaces are also the leading cause of urban flooding.

Flood Risks

Urban flooding is quickly becoming one of the most common and most expensive natural disasters to recover from (Merz et al, 2010). Municipalities and individuals are forced to endure most of the costs associated with flooding, which can be but are not limited to, high insurance costs, recovery efforts, maintenance, and higher taxes (Newkirk, 2000). In some cases, the hydrology in these areas has been permanently damaged and the problems are only exacerbated by the land maintenance practices and urban activity (Newkirk, 2000). The direct effects from flooding are apparent but the indirect effects that are laid upon other entities often go unnoticed (Merz et al, 2010). With flooding, the indirect effects can include the disruption of public services outside the flooded area, production loss for suppliers to the flooded region, costs of traffic disruption, and intangible trauma that affects the loved ones of those affected (Merz et al, 2010). There are also issues with fairness concerning urban flooding. The downstream areas from urban settings regularly have more frequent and severe floods than normally expected, and oftentimes more people are affected because of the high density of living spaces (Newkirk, 2000). Unfortunately, those involved in the construction of developed areas upstream in a watershed rarely consider the effects of their actions on anybody downstream from them and problems often arise (Newkirk, 2000). The flooding associated with impervious surfaces usually does not affect those in the immediate area; sometimes it travels downstream and can damage property and even take the lives of those who are unprepared for such an event (Newkirk, 2000). In many locations, people who are economically wealthier live upstream or in higher elevation compared to people with lower income, who live downstream and downhill (Walker & Burningham, 2011). Rampant upstream development largely disregarded the effects that the lower socioeconomic class was forced to bear because of the lack of repercussions (Walker & Burningham, 2011). Today, most construction efforts are held accountable for any effects stemming from their development (Walker & Burningham, 2011). Companies now look to city planners and engineers who have developed many techniques to mitigate stormwater and its destructive effects.

Management Techniques

There are many different ways to manage stormwater and mitigate its effects. Some techniques are better suited for flood control, while others are better at filtering out contaminants.

The management types that are being focused on in this research are porous pavement, capture basins, green roofs, rain gardens, rain barrels, and riparian zone repair.

Porous Pavement

Because of the negative effects associated with impervious surfaces, engineers designed a new type of surface that allows stormwater to infiltrate into the ground, while also retaining its purpose for vehicles. The result was permeable pavement that decreased the amount of stormwater runoff and water contamination (Brattebo & Booth, 2003). Permeable or porous pavement is commonly made up of asphalt or concrete blocks laid in a grid-like pattern with sand or gravel filling the spaces between (Brattebo & Booth, 2003). Plastic webbing forming a lattice structure can also be used underneath gravel, sand, or soil as a type of permeable surface (Brattebo & Booth, 2003). The purpose of the filled voids in between the plastic or blocks is to allow the stormwater to infiltrate into the soil where it can be absorbed and no longer causing a threat (Brattebo & Booth, 2003). Some types of permeable asphalt (which usually has at least 20% proportion of pores) allow the water to drain into the top layer of the pavement and then redirect it to the road's edge rather than straight down (Pagotto et al, 2000). Aside from the benefits to stormwater mitigation, porous roads benefit vehicular safety as well. Porous asphalt diminishes the chances of hydroplaning and increases the visibility while driving, both of which reduce the risk of a crash during heavy rainfall (Pagotto et al, 2000). Also, traffic noise levels are 3-4 dB lower on a porous surface than on a typical highway (Pagotto et al, 2000). Although it is a good way to manage flooding, most research shows the permeable pavement is better suited for increased ground infiltration (Scholz & Grabowiecki, 2007). In particular, permeable pavement is excellent at removing suspended solids and nitrogen from runoff (Scholz & Grabowiecki, 2007). Permeable pavement is meant to manage a drainage area from ¼ to 10 acres and is best suited for slopes less than 5% ("Water quality-stormwater management," 2013). It also should be placed on top of soil that is at least semi-permeable, having less than 40% silt/clay makeup ("Water quality-stormwater management," 2013).

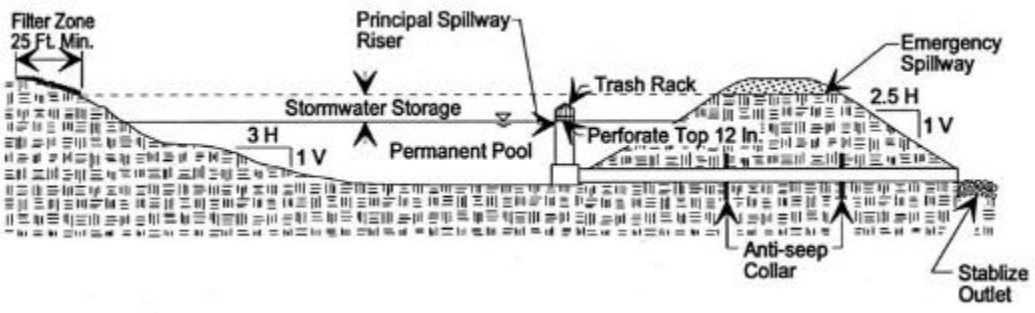
Unfortunately, there are also some drawbacks associated with replacing regular road surfaces with porous ones. Typical asphalt used in parking lots and roads costs about $.50 to $1 per square foot and the permeable counterpart costs anywhere from 25-300% more than that depending on type and quality (Booth & Leavitt, 1999). Permeable pavement might be cheaper

for total project costs in the long run though, because other stormwater management techniques might not have to employed (i.e. detention basin) (Booth & Leavitt, 1999). The permeable surfaces fail under black ice conditions and often need to be de-iced more often than normal roadways (Pagotto et al, 2000). High pressure rinsing must also be done frequently on low traffic roads due to the voids becoming clogged and sediment settling (Pagotto et al, 2000). In addition, permeable pavement is better suited for parking lots and residential streets because the roads cannot withstand high traffic volumes (Ferguson, 2005). Even with its disadvantages, porous road pavement is a viable option for stormwater mitigation.

Detention/Retention Basins

Another type of stormwater mitigation is the practice of building detention basins specifically for the improvement of stormwater quality and reduction of runoff flow quantity (Sayre et al, 2006). There are many different designs and purposes for the basins, but only a handful qualify as a "best management practice" (BMP) by professionals. Traditional stormwater detention basins (SDBs) help control flooding by retaining water at peak flow times and releasing it slowly into an outlet structure or stream (Sayre et al, 2006). The difference between traditional and the best management practice for SDBs is that the BMP-SDB takes its design a step further and not only controls flooding, but also filters pollutants by absorbing and dispersing them into retention areas (Hogan & Walbridge, 2007). The SDB-BMPs are constructed by taking advantage of the slope and elevation of the land to capture runoff and provide natural vegetation for the disruption and absorption of contaminants (Hogan & Walbridge, 2007).

Figure 2: Retention Basin (Sayre et al, 2006)



If the basin controls and filters the stormwater and then slowly releases it outwards, it is a detention basin; if the basin has a permanent pool of water that is being retained, it is a retention basin (Sayre et al, 2006). Retention basins (Figure 2) are often more effective at pollutant removal, especially when there is an abundance of aquatic vegetation (Sayre et al, 2006). Detention basins are especially good at redirecting stormwater overflow into a safer area while also performing some light filtering (Hogan & Walbridge, 2007). Not only are stormwater retention basins an excellent measure against flooding and pollution, their aquatic vegetation provides habitat for wildlife and is aesthetically pleasing. SDB's are meant to manage a developed area between 20-50 acres and have the ability to capture the first ½-1 inch of runoff that occurs during a storm event ("Water quality-stormwater management," 2013). A vegetative buffer around the basin of at least 25 feet is necessary for safety and root absorption on any SDB ("Water quality-stormwater management," 2013). Ponds can be placed on a slope up to 15% and can be used with all soils and geology ("Dry detention ponds," 2006). There are limitations associated with storm water detention ponds. They can be very costly, averaging anywhere from $41,000-100,000 for a 1 acre-foot pond ("Dry detention ponds," 2006). Most ponds in existence today do not meet the best management practice standards and therefore are lackluster at filtering toxins compared to other management systems ("Dry detention ponds," 2006). In addition, dry ponds that do not have aquatic vegetation or aesthetics have been known to decrease property value ("Dry detention ponds," 2006).

Green Roofs

Parking lots and roads are not the only type of impervious surfaces that lead to stormwater runoff; roofs are also a large type of impervious cover (VanWoert et al, 2005). Many metal roofs are covered in a zinc layer that can get washed away over time and carried away by runoff (Arnold & Gibbons, 1996). By vegetating the rooftops of buildings, stormwater can be mitigated through pre-existing structures. Not only does green roofing mitigate stormwater, it reduces energy consumption by better insulating the building, it increases the durability of a roof by shielding it from UV light and damage from extreme temperatures, it filters air pollutants, provides habitat for wildlife, and is visually appealing (VanWoert et al, 2005). The types of vegetation vary from small gardens to roofs that are totally covered by plants (Sayre et al, 2006). The green roofing is made up of multiple layers; there is a waterproofing and root barrier layer, a drainage and filter layer, the soil and plants, and an optional insulation layer (Sayre et al, 2006).

Once the roof has absorbed the water, it can hold it for a period of time and slowly release it at a manageable rate (VanWoert et al, 2005). Depending on the type, green roofs are estimated to be able to retain 60-100% of rainfall for a given precipitation event (Monterusso et al, 2004). A study by Graham and Kim (2003) suggest that if every roof in Vancouver, Canada were retrofitted with green roofing, the local watershed would return to its natural conditions. Green roofs can be categorized into two subtypes, extensive and intensive (Bliss, 2004). Intensive green roofs are generally built on larger buildings that are able to withstand the enormous amount of weight that comes with it (Bliss, 2004). Intensive green roofs can be tourist attractions and usually have large shrubs or trees planted (Bliss, 2004). The depth of the soil can sometimes be over a foot with intensive roofs (Bliss, 2004). These types of roofs are extremely costly, require high maintenance and extensive irrigation, and are exceptionally heavy. Extensive green roofs are more practical and more prevalent throughout the world (Bliss, 2004). They are more garden based and only have soil reaching 6 inches deep at most (Bliss, 2004). Extensive green roofs are not as stressful to the building's structural integrity, need less maintenance, and are much cheaper than intensive green roofs (Bliss, 2004). Most green roofs can be implemented on roofs that slope up to 20% with 40% being the absolute limit ("Green roofs," 2006). They are most appropriate for commercial or industrial buildings but can also be used in large residential complexes ("Green roofs," 2006). Some limitations include the high cost of construction and the constant maintenance, depending on the type of system implemented ("Green roofs," 2006). The average cost of an extensive green roof is $10 per square foot and for intensive green roofs; it is $50 per square foot ("Green roofs," 2006). Although green roofs are relatively new to the United States, they are a worthwhile technique for urban stormwater mitigation.

Other Techniques

A wide variety of stormwater management options exist that can be specifically catered to any situation. The aforementioned techniques mostly described ways to manage stormwater in an urban setting, but residential areas require different methods. On their own, residential and suburban neighborhoods tend to have a smaller impact compared to large urban centers, but sudden large-scale residential development can be just as problematic. Luckily, the management

options for neighborhoods are cheaper and easier to implement. Rain gardens are a form of bioretention that allow stormwater to infiltrate the soil, filtering out pollutants and reducing peak flow in the process (Dietz & Clausen, 2005). Trees or shrubs are planted in depressions in the ground layered with permeable soil or mulch (Dietz & Clausen, 2005). When heavy rainfall occurs, runoff is caught in the garden and slowly is absorbed into the soil or into the roots of the plants (Dietz & Clausen, 2005). Rain gardens are most appropriate for parking lots or within residential neighborhoods (Dietz & Clausen, 2005). The drainage area that rain gardens have the ability to manage is relatively small, only about 5 acres or less ("Bioretention (rain gardens)," 2006). Rain gardens can be placed on any soil type but cannot be on a slope greater than 5% ("Bioretention (rain gardens)," 2006). The cost of rain gardens varies greatly depending on the size, plants, and effectiveness but overall is a cheaper form of mitigation compared to others ("Bioretention (rain gardens)," 2006).

Rain barrels are another inexpensive but useful form of stormwater management that work great in residential environments. Rain barrels are designed to catch drainage from rooftops and store the water for later reuse for watering lawns (Hager, 2003). They come in many different sizes and are relatively cheap, ranging from 15-200 dollars (Hager, 2003). Rain barrels can be put anywhere as long as a gutter directs the water into them (Hager, 2003). Barrels do not provide any direct improvement to water quality, but capturing excess water indirectly mitigates contamination by keeping it off the road. Alone, the use of rain barrels is not enough to adequately manage stormwater but when used with other techniques such as rain gardens, it can be a useful tool (Hager, 2003).

With regards to stream health, nothing is as important as an intact riparian zone buffer (*Riparian buffers*). The riparian zone is the land adjacent to a water body that contains vegetation that acts as a filter (*Riparian buffers*). Deep-rooted trees and shrubs absorb limited amounts of runoff water and can uptake pollutants before they reach the surface water (*Riparian buffers*). A healthy riparian buffer should range from 25-100 feet wide on each side of the stream (*Riparian buffers*). It costs roughly $2000 per acre to fully repair a depleted riparian zone, but the benefits greatly outweigh the costs, especially when compared to the prices of other management techniques (Butler, 2005). Riparian zone depletion in a residential setting often goes overlooked

and but repairing them could prove to be beneficial against stormwater problems in the long run (Butler, 2005).

Pittsburgh Stormwater

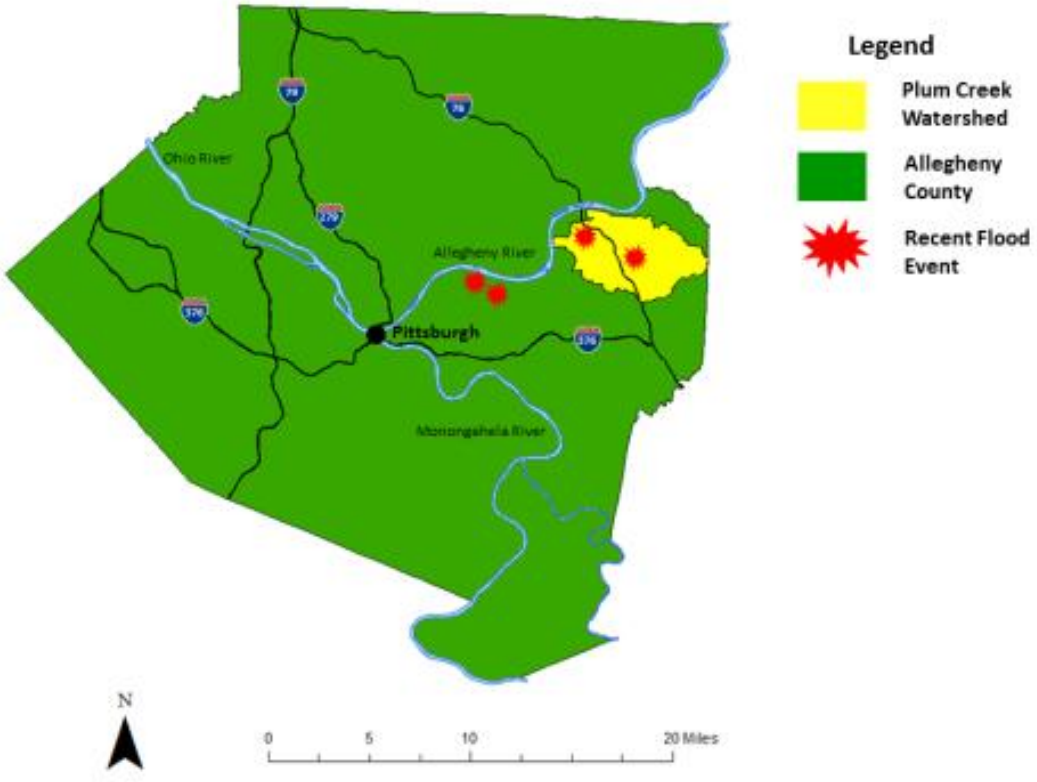
Over the course of history, the city of Pittsburgh, Pennsylvania has seen its fair share of pollution problems. Luckily, most of those problems have been solved but a few still remain. Stormwater management is one of the problems that Pittsburgh has still yet to overcome. Like many other old cities in the United States, Pittsburgh still uses a combined sewer system. A combined sewer system is one that handles both raw sewage and stormwater (Bliss, 2004). The main problem associated with combined sewer systems is that during heavy rainfall events, the treatment plants become overwhelmed with incoming stormwater and are forced to release raw sewage into rivers in order to make room for the incoming flow (Bliss, 2004). The dumping of raw sewage into rivers with aquatic life is devastating to the biodiversity of the ecosystem (Bliss, 2004). Mitigation approaches that are mainly concerned with flood control would greatly help the burden of sewer overflow (Sayre et al, 2006).

Recently, flash flooding has been brought to the forefront of issues that need to be solved in Pittsburgh after several people were killed along Washington Boulevard by flooding caused by stormwater (Balingit, 2013). Multiple lawsuits have arisen since the incident, naming the city of Pittsburgh, Pittsburgh Water and Sewer Authority, the state Department of Transportation, and Alcosan stormwater management liable for the deaths (Balingit, 2013). In a possible response to the severity and frequency of flooding in urban Pittsburgh, the EPA awarded the city $75,000 to put towards stormwater mitigation initiatives (Hopey, 2012). Since the city was granted money for stormwater control techniques, I believe it could benefit from an analysis showing areas that are most suitable for mitigation technology in the watershed of a tributary of the Allegheny River so that downstream flooding and water quality can improve.

Urban areas like the ones found near Washington Boulevard are at the mercy of the events taking place upstream. To decrease the total amount of water entering the Allegheny River and to mitigate contamination, upstream watersheds need to be managed carefully (refer to Figure 3 for an overview of Allegheny County). Areas upstream that are recently developed are very problematic because of the rapid buildup of stormwater that enters the system after new

construction projects are undertaken. To help provide insight into possible solutions for the problem, I conducted several GIS suitability analyses that aim to help make recommendations for the recently developed Plum Creek watershed, upstream of Washington Boulevard.

Figure 3: Allegheny County

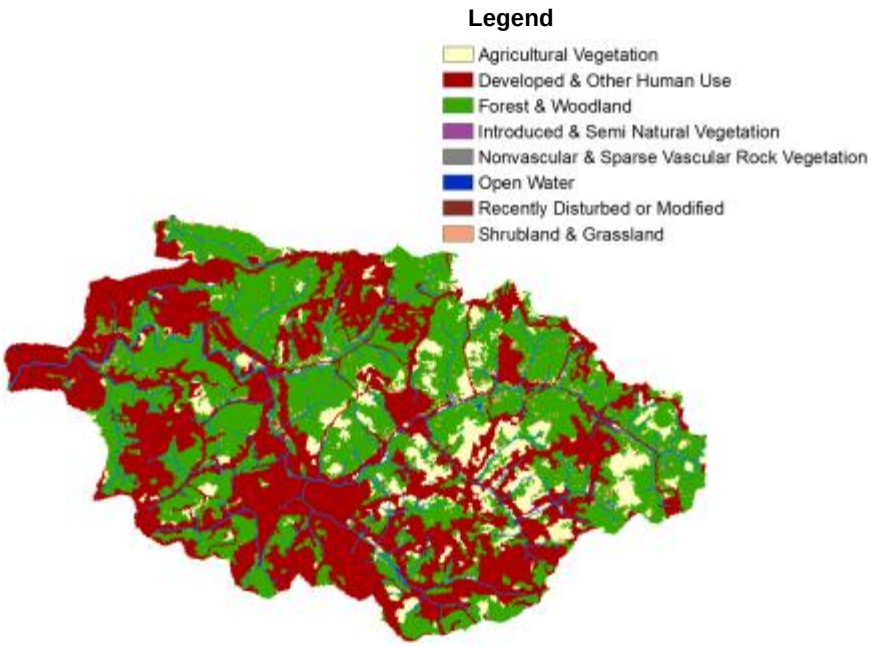


Methods

Study Site

The Plum Creek Watershed is located in southwestern Pennsylvania, east of Pittsburgh. It is within Allegheny County and is approximately 20.6 square miles. The watershed lies within the boroughs of Verona, Oakmont, Plum, and Penn Hills. There are two main streams within the watershed, Plum Creek and Little Plum Creek. Plum Creek drains into the Allegheny River near Oakmont, Pa. It flows from the southeast to the northwest and the elevation ranges from 1300 feet at the headwaters to 721 feet at the river. The major land use around Plum Creek is suburban residential development but there is also forested land and commercial/industrial development. Little Plum Creek is a tributary to Plum Creek, joining Plum Creek near the community of Unity. It flows from east to west and the elevation ranges from 1300 feet to 960 feet. The major land use around Little Plum Creek is undeveloped farmland and forested land, minor land uses include residential areas and reclaimed mine sites. Figure 4 displays a map of the watershed and its major land uses.

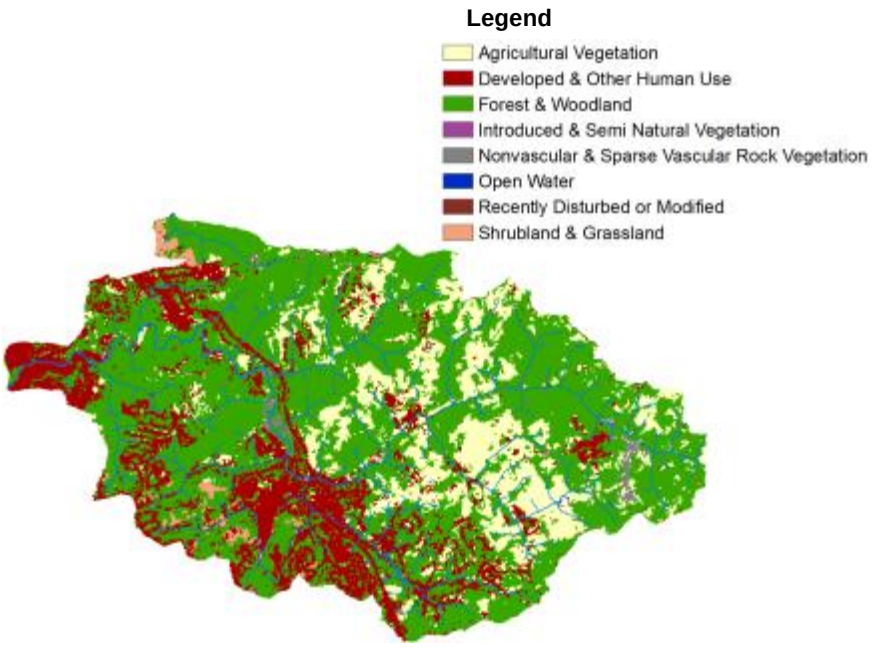
Figure 4: Plum Creek Watershed 2006 Land Cover



In 2003, a Total Maximum Daily Load (TMDL) was developed in compliance with a Pennsylvania/EPA agreement to limit the amount of pollutants that can enter the Plum Creek Watershed. This watershed was highlighted because of the high concentrations of metals and an acidic pH, most likely from acid mine drainage. The Plum Creek Watershed is also on the PA Section 303(d) list for nutrient, oil and grease, and siltation impairments resulting from Urban Runoff/Storm Sewers and Combined Sewer Overflow. No formal management plans exist for stormwater management in the Plum Creek Watershed.

The Plum Creek Watershed is roughly twenty miles upstream of many flood events that have happened along Washington Boulevard. Over the last several decades, the major land uses in the watershed have changed from being primarily agriculture and forest; to being residential/commercial development (refer to Figure 5). The sudden construction of impervious pavement and creation of bare soil is impairing the water cycle by producing excess runoff that can cause flooding and water pollution. Being one of the few watersheds that do not have a management plan, implementing forms of stormwater mitigation techniques will reduce the rate of flooding and improve overall health of the watershed and the Allegheny River. This study aims to produce maps showing suitability for different stormwater mitigation systems so that several management plans can be implemented for the Plum Creek Watershed.

Figure 5: Plum Creek Watershed 1992 Land Cover



GIS Data Collection

Spatial datasets were collected through various online databases (Table 1) for use in the GIS program, ArcMap 10.1. I edited and cut down the variables so that they were specific to the Plum Creek Watershed before any analyses took place. Spatial data was found in two forms, vector and raster. Vector data describes spatial features such as points, lines, and polygons that have a defined existence on the X-Y plane. Raster data describes images that are made up of pixels, each of which have an assigned value in the GIS. For this project, most of the datasets that were collected were converted to raster in order for manipulation and uniformity.

Table 1: Data Layers and Sources

Feature	Data Name and Source
Plum Creek Watershed	Pennsylvania Watersheds- PASDA
Porous Pavement	Landcover, Soil, Slope - USGS
Stormwater Basins	Slope, Landcover- USGS
Green Roofs	Allegheny County Building Footprints- PASDA
Rain Gardens	Slope, Landcover- USGS
Riparian Zone Repair	Hydrology- USGS

Suitability Analysis

Each management type was tested for suitability within the watershed. Suitability was determined by ranking certain criteria on a scale from 1-5, 5 being most suitable for management implementation. The "reclassify" tool was used to rank the variables within a dataset on a common scale. The weighted sum tool was used to combine data layers and to give them a weight signifying importance. Overall justification for the criteria ranks is given below for each type of management. In some cases, particular management strategies were not feasible and so any criteria that are not listed in the tables below were not included in the analysis.

The purpose of these suitability analyses is to use the results in order to make informed recommendations for stormwater management in the Plum Creek Watershed. The maps that were created should be considered as a starting point for the discussion on stormwater mitigation efforts. Recommendations will be based on the results of multiple analyses and on patterns between maps.

Porous Pavement

Porous pavement is recommended to be placed on top of semi-permeable soil with as little silt and clay as possible ("Water quality-stormwater management," 2013). The better drained the soil is, the more suitable the land will be for porous pavement. Table 2 displays the soil drainage and the rank given for the analysis.

Table 2: Porous Pavement Soil Drainage

Rank	Soil Drainage
5	Well Drained
4	Moderately Well Drained
3	Somewhat Poorly Drained
2	Poorly Drained

Porous pavement should be placed on relatively flat land so that it can perform at its duty optimally ("Water quality-stormwater management," 2013). Slopes higher than 10% were not considered in the analysis because it severely increases construction costs. Table 3 presents the rank that the slope was given for porous pavement.

Table 3: Porous Pavement Slope

Rank	Slope %
5	0-5%
3	5-10%

Once the soil and slope variables were reclassified, each variable was given a weight that would correspond to its importance in the suitability analysis. The soil drainage variable held 75% of the weight and the slope was given 25%.Having good soil drainage beneath the road is important so that water will not accumulate and create dangerous conditions.

Porous pavement is more suitable on roads with low traffic levels because it requires less maintenance and there is less sediment buildup in the pores (WSDOT, 2010). Parking lots have a sizeable effect on the creation of runoff and are therefore very suitable for porous pavement

implementation (WSDOT, 2010). The larger the parking lots, the better it will be for porous pavement due to its high cost of construction. Residential and some commercial areas do not have their daily traffic count recorded because the values are so low, so these areas were the ones considered in the analysis. Once the suitability analysis was finished, I used the extract by mask tool to erase all areas that were not residential or commercial land use so that only the low traffic roads and parking lots were considered.

Stormwater Basins

Stormwater basins are better suited for smaller slopes because construction costs increase if the land requires additional excavation ("Dry detention ponds," 2006). A completely flat slope is undesirable because the infiltration mechanism will not work properly. The rank and slope percentage can be found in Table 4. In the suitability analysis, the slope data was given 50% weight.

Table 4: Stormwater Basin Slope

Rank	Slope %
5	2-4
4	3-6
3	6-9
2	12-15
1	0-2

Basins should be close to development to efficiently capture the drainage created ("Water quality-stormwater management," 2013). Development that creates more toxicity and runoff is more desired for basin placement. Table 5 displays the rank and specific land covers that were considered in the analysis. The land cover variable was weighted equally in the suitability analysis with the slope because of their equal importance.

Table 5: Stormwater Basin Land Cover

Rank	Land Cover
5	Commercial
4	Industrial
3	Residential
2	Open Space
1	Other

Green Roofs

Green Roofs are most suitable on bigger buildings that are either commercial or multi-residential ("Green roofs," 2006). This study assumes that the roofs of bigger buildings have a higher load potential. The sizes of the roofs and the corresponding rank are found in Table 6. Since there was only one variable in this analysis, no weights had to be given.

Table 6: Green Roof Size

Rank	Roof Size (Sq ft)
5	>10,000
4	7,000-10,000
3	4,000-7,000
2	2,000-4,000
1	700-2,000

Rain Gardens

In order to properly catch runoff, rain gardens must be constructed on relatively flat slopes ("Bioretention (rain gardens)," 2006). The slope of the land and its rank for the analysis is found below in Table 7. The slope dataset was given a weight of 50% for the suitability analysis.

Table 7: Rain Garden Slope

Rank	Slope %
5	0
4	1-2
3	3
2	4
1	5

Rain Gardens are most suitable in residential areas because of the aesthetics and low management capabilities ("Bioretention (rain gardens)," 2006). Table 8 displays the suitable land covers and their individual ranks. The land cover input was also given a 50% weight in the suitability analysis.

Table 8: Rain Garden Land Cover

Rank	Land Cover
5	Open Space (Developed)
4	Residential Development
3	Commercial Development
2	Industrial Developed

Riparian Buffer Health

Intact riparian zone buffers filter pollutants through root uptake and are a useful tool in managing stormwater. Riparian zones that are completely depleted are most suitable for repair because nothing is stopping the water from flowing directly into the adjacent stream. This dataset was manually created using the hydrology data for the watershed and satellite imagery. The satellite imagery provided a visual representation of the riparian zone health. I made buffers around the stream network at 50,40,30,20, and 10 meters. I then gave the stream segment a ranking based on how much vegetation buffered the edge on *both* sides of the water. The criteria and rank for riparian zone health is in Table 9. No weight was given to this data because it was the only variable.

Table 9: Riparian Zone Health

Rank	Riparian Health
5	Excellent (Vegetation > 40 meters)
4	Good (Vegetation 30-40 meters)
3	Okay (Vegetation 20-30)
2	Poor (Vegetation 10-20)
1	Depleted (Vegetation 0-10 meters)

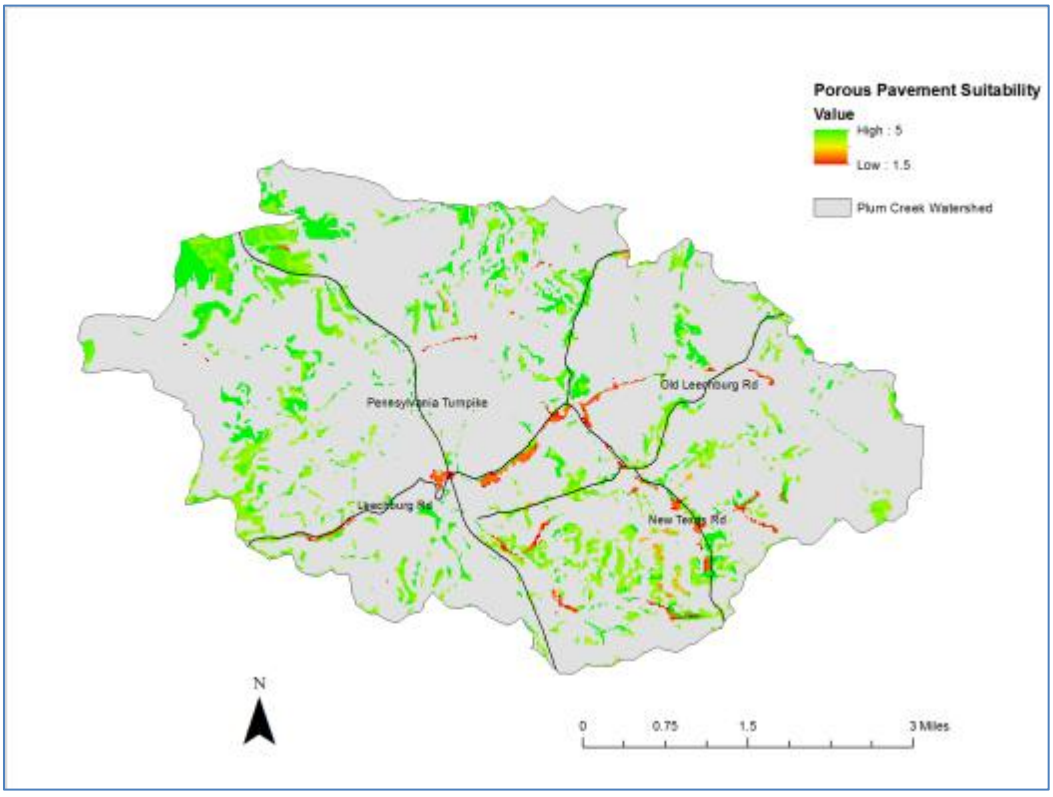
Results

The results of the GIS suitability analyses are depicted below. Each map consists of the Plum Creek Watershed and the suitability for each respective form of stormwater management. Suitability was ranked from 1-5, 5 being the highest. High suitability corresponds to a dark shade of green and the darker shades of red show low suitability. Any area that is gray was not considered in the suitability analyses because the input data did not meet the specified parameters and therefore could not be considered. Main roads are highlighted for reference in most of the maps.

Porous Pavement

The results of the porous pavement suitability analysis (Figure 6) show strong suitability in the northwest corner of the watershed. Roads that receive heavy traffic were not considered, so residential neighborhoods and parking lots make up most of the higher suitability areas. There is not much variability in the suitability in this map; it appears that areas are either highly or poorly suited, with little room in between.

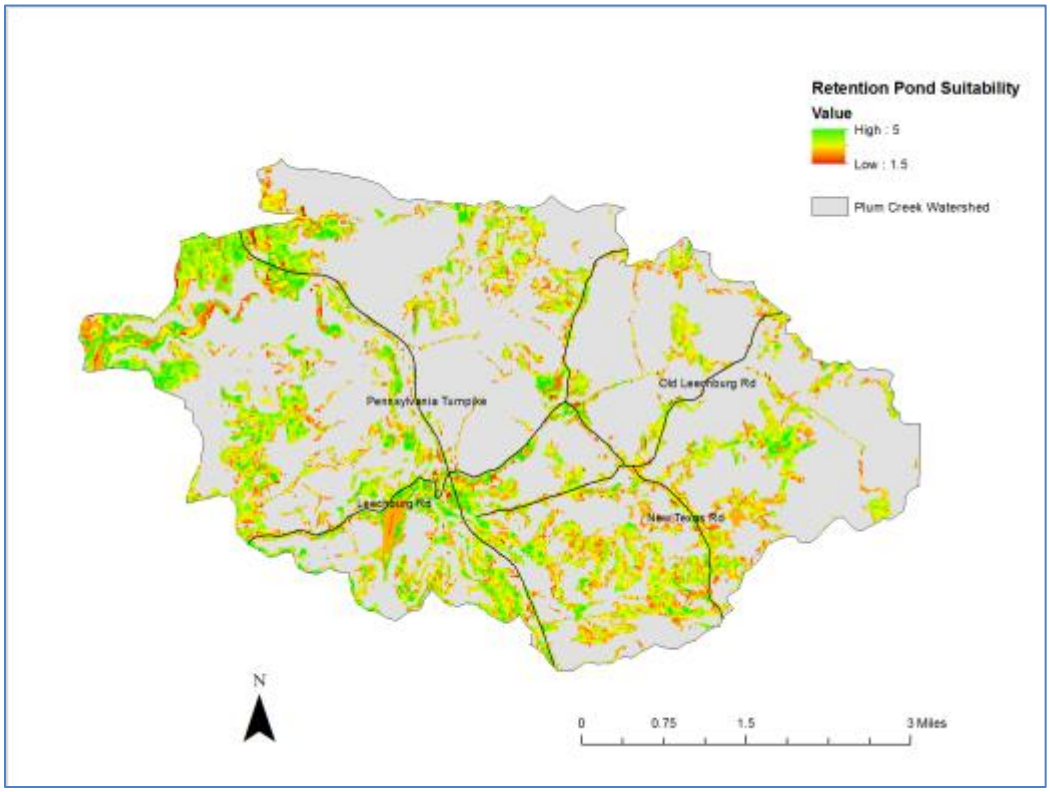
Figure 6: Porous Pavement Suitability



Stormwater Basin

The results of the stormwater basin suitability analysis (Figure 7) are more varied than the porous pavement results, but both maps show high suitability scores in the northwest corner. There was also high suitability around the intersection of Leechburg Road and the Pennsylvania Turnpike.

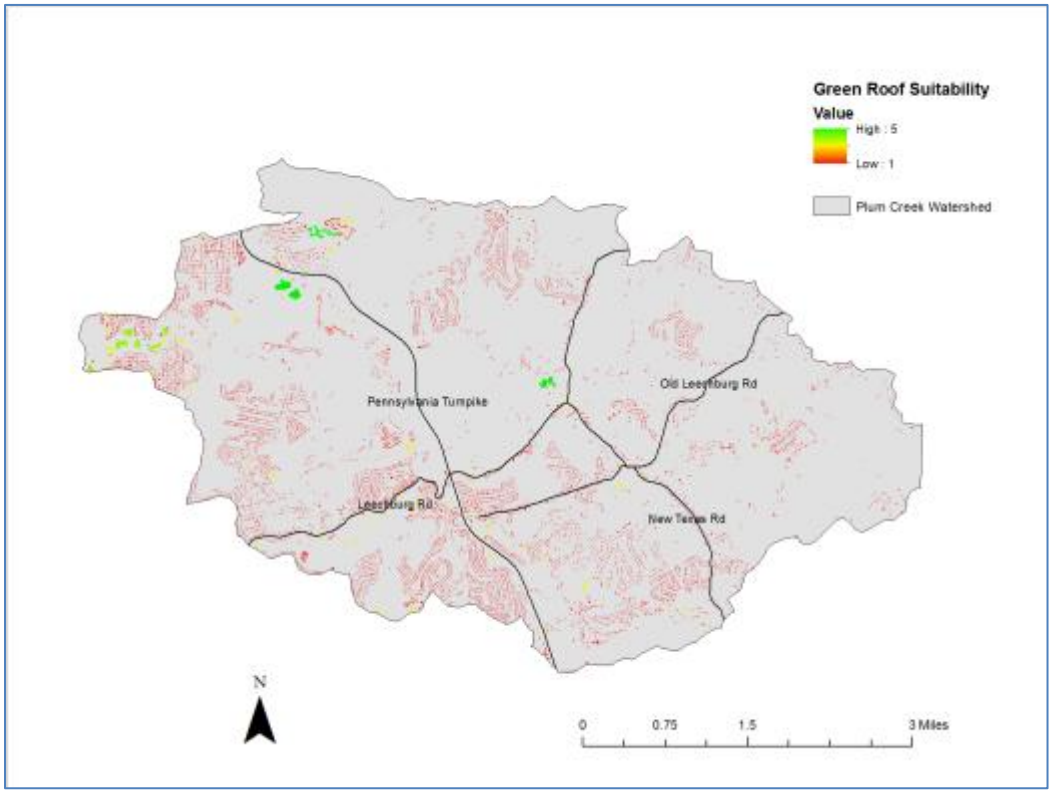
Figure 7: Stormwater Basin Suitability



Green Roofs

The green roof suitability analysis (Figure 8) displays only several options for green roof retrofitting. Most buildings that are highlighted for excellent suitability are large commercial or industrial buildings. In the center of the watershed, Plum Senior High School is deemed suitable for green roof retrofitting. There is an abundance of low suitability roofs that are highlighted, most of which are residential and not ideal for retrofitting. Single family housing units dominate this watershed, which is the reason there are so few ideal candidates.

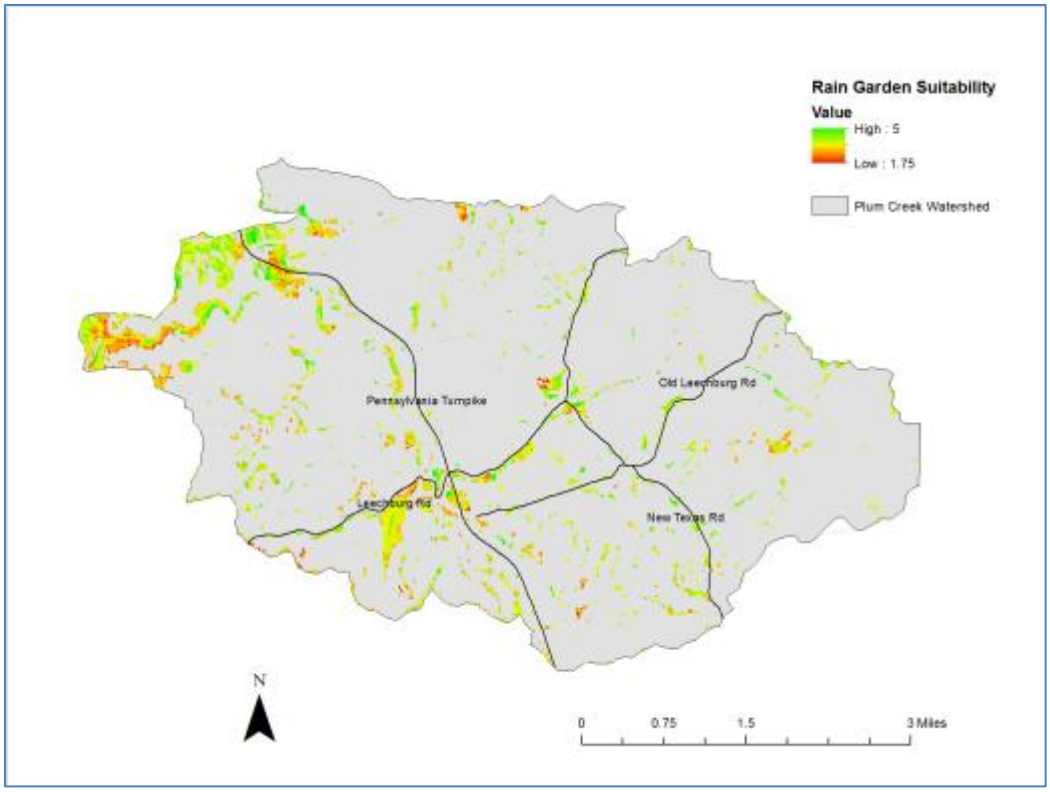
Figure 8: Green Roof Suitability



Rain Gardens

The rain garden suitability analysis (Figure 9) displays similar results to that of the porous pavement and retention basin maps. The biggest cluster of high suitability areas is found in the northwest. The total area that is ranked for rain gardens is fairly small, most likely due to the strict slope requirements that rain gardens require. Realistically, rain gardens could be placed practically anywhere, but the goal of this assessment is to highlight land that needs very little to no additional landscaping in order for the rain garden to function properly.

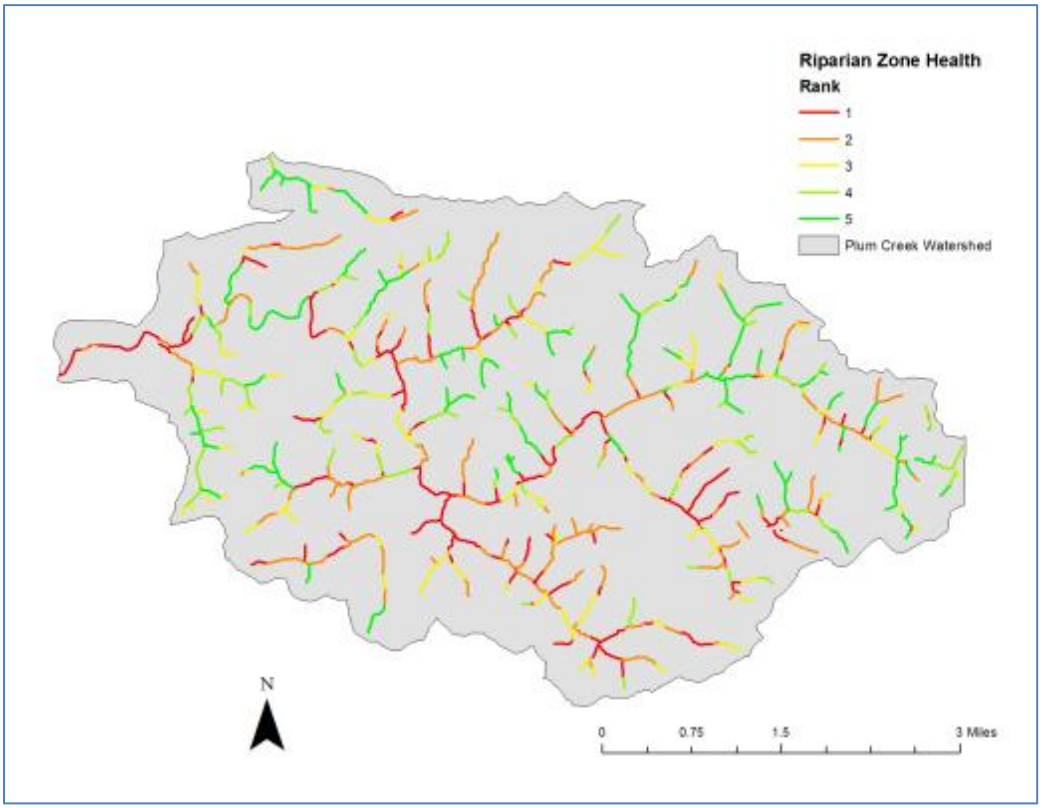
Figure 9: Rain Garden Suitability



Riparian Zone Health

This map (Figure 10) displays the health of the riparian zone buffer in the stream network. There is a total of 76.22 miles of stream in the Plum Creek Watershed. Stream segments with excellent riparian zone health (rank 5) make up 15.99 miles of the total stream network. Riparian zones given a rank of 4 make up 10.12 miles of stream. Rank 3 zones account for 12.37 miles of stream. Rank 2 riparian zones make up most of the stream total with 19.96 miles. Lastly, riparian zones with poor health (rank 1) contribute to 17.78 miles of total stream length.

Figure 10: Riparian Health Suitability



Recommendations

The results of the suitability analyses provided spatial information on areas that are suitable for stormwater management. There were some patterns between maps that warranted further investigation using satellite imagery. For example, the northwest corner of the Plum Creek watershed displayed strong suitability for nearly all types of stormwater management systems based on the results of the GIS suitability analysis. The northwest corner includes mostly Plum Borough, but also includes parts of Oakmont and Penn Hills. This area is relatively lower in elevation compared to the rest of the watershed. The area also has gentle slopes and moderately well drained soil, making it suitable for nearly all mitigation efforts. The land cover can be described as mostly residential, as suburban-style neighborhoods dominate the landscape. Notable landmarks in the northwest corner of the watershed include Oakmont Country Club, a world-renowned golf course, and the Pennsylvania Turnpike, which nets roughly 40,000 vehicles through that stretch every day. Most of the recommendations deal with this part of the watershed because of the cluster of high suitability areas. Recommendations have been broken up into four separate plans that are based around a common theme (i.e. price, management type).

Residential Plan

This plan utilizes relatively inexpensive forms of stormwater mitigation that are intended for residential use. Rain barrels are an excellent form of cheap but effective stormwater management. One standard 55-gallon rain barrel is sufficient for every 500 sq. ft. of roof and costs around 80 dollars. Roofs that drain to down spouts are necessary for the rain barrel to function properly. For optimal performance, a landscaped area such as a rain garden is recommended because the stormwater can be reused for irrigation. The mitigation potential is increased when rain barrels are paired with the use of rain gardens because gardens have the ability to filter contaminants and further reduce peak flow. The cost of rain gardens varies, but it is still relatively low compared to other forms of stormwater removal.

Rain barrels were not included in the suitability analysis because it is impractical to assess feasibility without an on-site assessment. In addition, most suburban houses are good candidates for rain barrels. Houses that are in proximity to land that has been deemed suitable for rain gardens should receive rain barrels due to their synergistic nature. There were two distinct sites in the northwest (Appendix Figure 1 and 2) that were most suitable for rain gardens.

Site A (Figure 11) is a development that is found in the Borough of Oakmont comprised entirely of townhouses. The houses have almost identical features, which include large roofs and ample green space. Management efforts are ideal for this area because of the large amount of imperviousness created by the roofs and also because the open green space could be used for rain garden placement. Since the residents of the neighborhood are lessees, the owner of the community could institute a rain barrel policy or transform some public space into a garden.

Figure 11: Plan #1 Site A



Site B (Figure 12) is also found in Oakmont and scored very highly in the suitability analysis for rain gardens. It contains a combination of three separate housing styles that would work well with the "low cost" approach. The first housing style, another townhouse community, is found in the far eastern corner of Site B. This makes it appealing for garden and barrel management for the same reasons as Site A, stated above. The second housing style is at the very top of Site B and contains large, brand new houses. Their roofs are large and therefore carry a large potential for runoff creation. Since the development is brand new, the ground has been recently disturbed and very little vegetation remains. The lack of trees and shrubs is an important reason why rain gardens should be implemented, so that runoff can be absorbed by the roots. There is plenty of space for rain gardens, but it should be noted that the land is privately owned.

The last style of housing is the one that envelopes most of Site B. These are middle-sized houses, packed closely together, and with a good amount of vegetation intermixed. Smaller rain gardens would work better here compared to bigger ones because of the lack of space between houses. While the roofs may be smaller in comparison, these houses carry a large potential for runoff due to the large amount of homes in proximity to one another. Managing Site B will be a more extensive and costly undertaking than Site A due to the size difference, but it will also yield greater stormwater mitigation.

Figure 12: Plan #1 Site B



Commercial Plan

This plan provides recommendations for stormwater mitigation at the commercial level. It costs more than the residential plan because its main focus is to use porous pavement to manage runoff. When used correctly, porous pavement has the potential to be a powerful tool against stormwater. The cost of porous pavement ranges significantly based on the type of materials used. For this plan, only one site (Appendix Figure 3) was highlighted for porous pavement retrofitting due its extraordinary suitability.

Site A (Figure 13) is the location of the Longwood at Oakmont community. Longwood at Oakmont is a LEED Silver certified retirement community that occupies a 52 acre campus on the edge of Plum Borough. The directors of the community and the residents place a high importance on environmentally friendly activities. I recommend the addition of stormwater mitigation efforts on the campus due to the previous "green" efforts made by the community and also because of its high suitability based on the GIS analysis. There is about 385,000 sq. ft. of impervious pavement in the community that can be retrofitted to be porous. In addition, there are also suitable areas separating the parking lots for rain gardens.

Figure 13: Plan #2 Site A



Intensive Plan

This proposal involves using green infrastructure that is generally very expensive and requires a greater deal of care and maintenance. Two types of stormwater management styles were considered for this plan: green roofs and stormwater basins. Based on the suitability criteria, there were only several buildings in the watershed that were feasible for green roofs. Upon further investigation, even fewer were considered suitable based on the slope of the roofs. It is difficult to estimate the price of a green roof because there is so much variation, but on average it is much more expensive than most types of stormwater mitigation because of the size

and the scope of the project. The price of retention basins are also difficult to estimate because of the nuances of the engineering and site specificity. What green roofs and retention basins lack in economic practicality, they make up for in runoff reduction and contaminant removal. Two sites (Appendix Figures 4 and 5) were highlighted in this plan, one for a stormwater basin and another for a green roof.

Site A (Figure 14) is one of the many areas that ranked highly for stormwater basin placement. What made Site A stand out was that it was at the foot of a large residential area and also directly on the edge of the Pennsylvania Turnpike. A basin at the foot of a residential development and near a large road system will be able to collect a great deal of water from the neighborhood and contaminants from automobiles. The homes also sit on a hill sloping downward toward the turnpike, making water catchment easier.

Figure 14: Plan #3 Site A



Site B (Figure 15) is not found in the northwest like most recommendations have been. Site B is Plum Senior High School, which is found in the center of Plum Borough. What makes this school a prime option for a green roof is the fact that it has multiple, large roofs in a single complex that are completely flat. It has high load bearing potential and can benefit from state and federal tax breaks for implementing a green roof. The Energy Policy Act of 2005 states that

federal tax credits of up to $1.80 per square foot are available for green projects that meet ASHRAE standards.

Figure 15: Plan #3 Site B



Riparian Zone Remediation Plan

This plan's aim is to remediate stream banks that have a degraded riparian zone. The most efficient way to repair a riparian zone is to revegetate the area so that the plants can absorb incoming water. The best management practice for revegetation is to use native plants because they are naturally built for the environment and will not outcompete the vegetation that already exists. Roots that can uptake a greater amount of water are better suited for the job than simple grasses. Larger plants are also better at obstructing large amounts of runoff as well.

For this plan, an entire section of the Plum Creek stream network was highlighted (Appendix Figure 6) for remediation. This section had mostly poor riparian zone health, but also had a large amount of development. In certain circumstances, it is impossible to revegetate an area because development has encroached so closely to the stream's edge. In this case, I recommend using porous pavement if applicable in order to reduce the amount of runoff flowing

freely into the stream. These areas pose a great threat to stream health because contaminants can enter the ecosystem with relative ease. The entire section should be looked into for remediation, but I highlighted two examples that represent the overall depletion of this stream's riparian zone.

Example 1(Figure 16) shows how development has reached the edge of the stream and plants can no longer offer protection. The parking lots highlighted in purple would be ideal candidates for porous pavement.

Figure 16: Plan #4 Example 1



Example 2 (Figure 17) displays an area that has sparse vegetation bordering the stream and some houses that encroach on the edge of the stream bank. This area would benefit from revegetation so that stream health could improve.

Figure 17: Plan #4 Example 2



Limitations

There are some limitations to this study that should be addressed. The placement of some of the stormwater management techniques simply cannot be determined solely by a spatial analysis. The spatial analysis merely provides a suggestion based on input variables backed by literature. Also, the cell size in some of the input layers was too large (30x30 meters) to pinpoint exact locations for suitability. Most of the suitability analyses are only aiming to display land that needs very little or no additional landscaping for green infrastructure to be implemented. Highlighting land that has inherent characteristics needed for stormwater management tools reduces the overall cost of construction. Some of the input data are outdated by several years and might not represent the current makeup of the Plum Creek Watershed, but this data was the best

available and offered the most accurate portrayal as possible. Also, it was beyond the scope of my project to more directly tackle financial costs and benefits of various proposals.

Conclusion

There is currently a lack of presence in the Plum Creek Watershed regarding stormwater management. Thirteen years ago, an organization called the Plum Creek Watershed Association was created in order to protect and improve the water quality in the watershed. The group was made up of members from the four boroughs in the watershed, Plum, Penn Hills, Oakmont, and Verona. This group is presently dormant and no longer formally exists. If the association ever became active again, it would benefit from the information found in this study. The local governments of the boroughs might also find this information useful for planning and stormwater management.

The Nine Mile Run Watershed Association is a group that protects the Nine Mile Run Watershed that exists several miles southwest of Plum Creek. The group has done an excellent job revitalizing the urban watershed and is a standard of excellence in the region. A branch exists within the association known as Pittsburgh Stormworks that solely deals with stormwater management. Stormworks' goal is to provide stormwater mitigation products to the entire Pittsburgh region. They offer rain barrels, gardens, riparian zone vegetation, and consultation on landscaping and installation of the products. This organization would be an excellent partner for any group looking to bring these recommendations to fruition.

Appendix: Site Overviews

Figure 18: Residential Plan Site A Overview

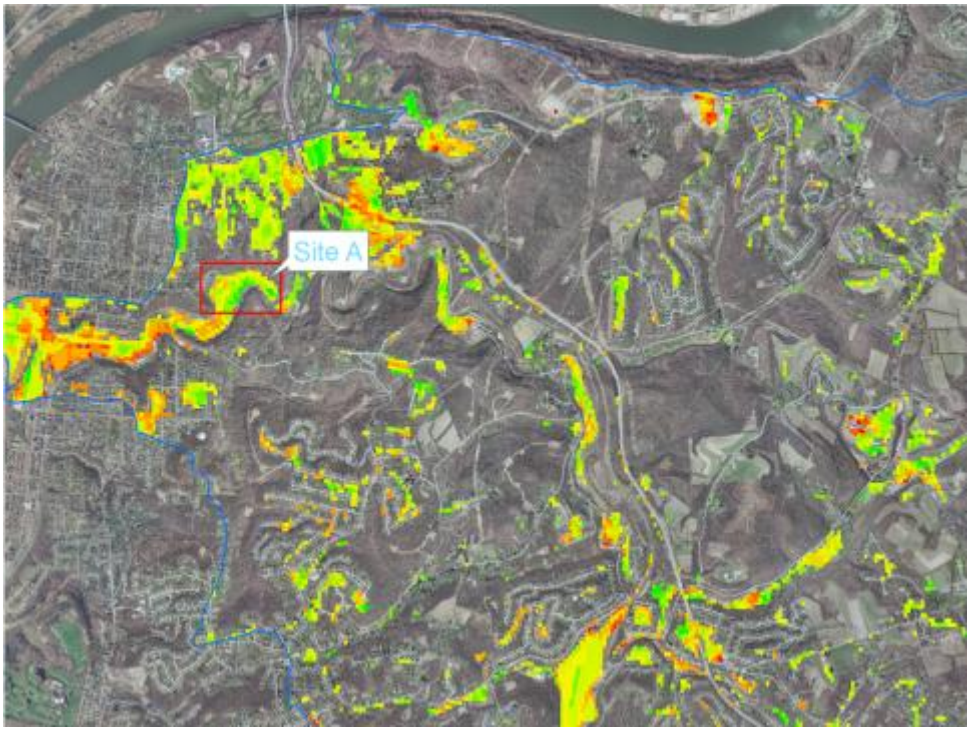


Figure 19: Residential Plan Site B Overview

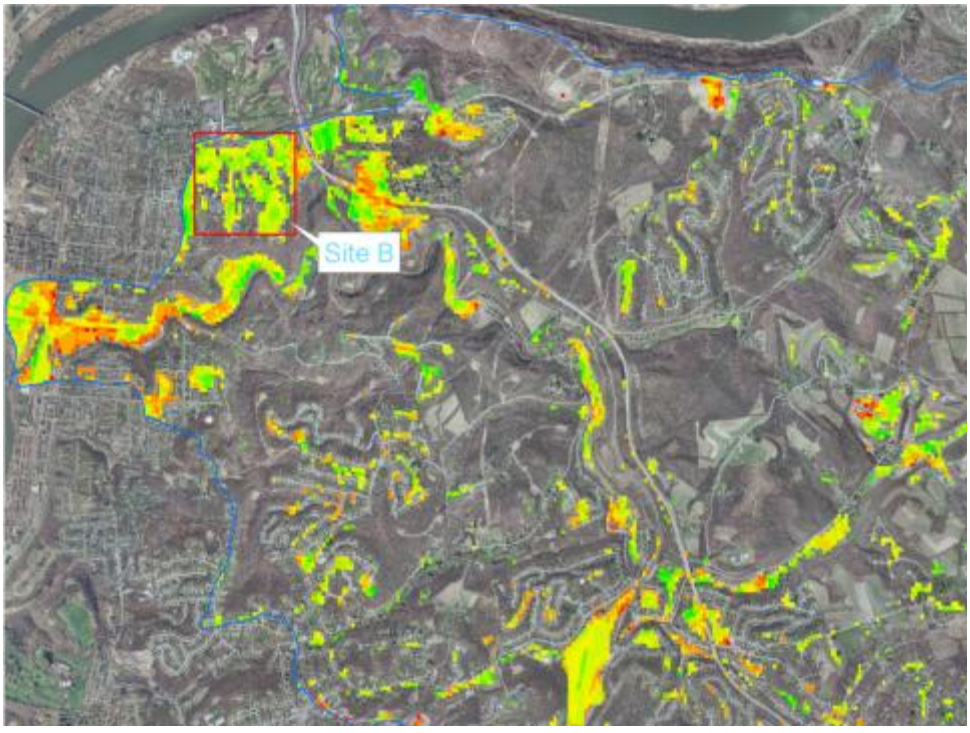


Figure 20: Commercial Plan Site A Overview



Figure 21: Intensive Plan Site A Overview

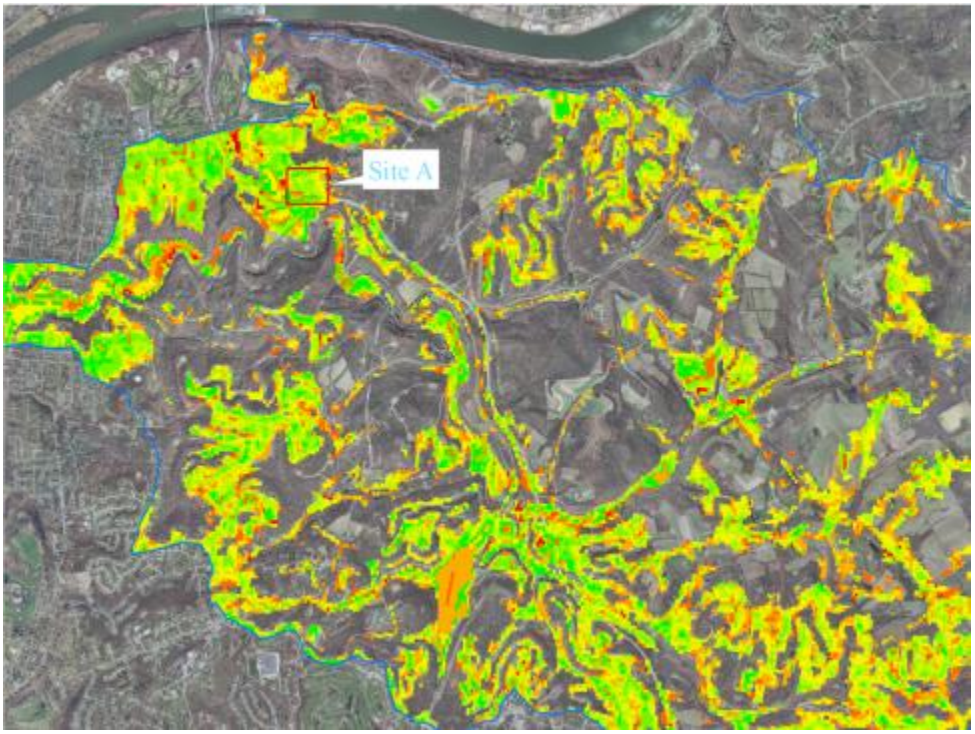
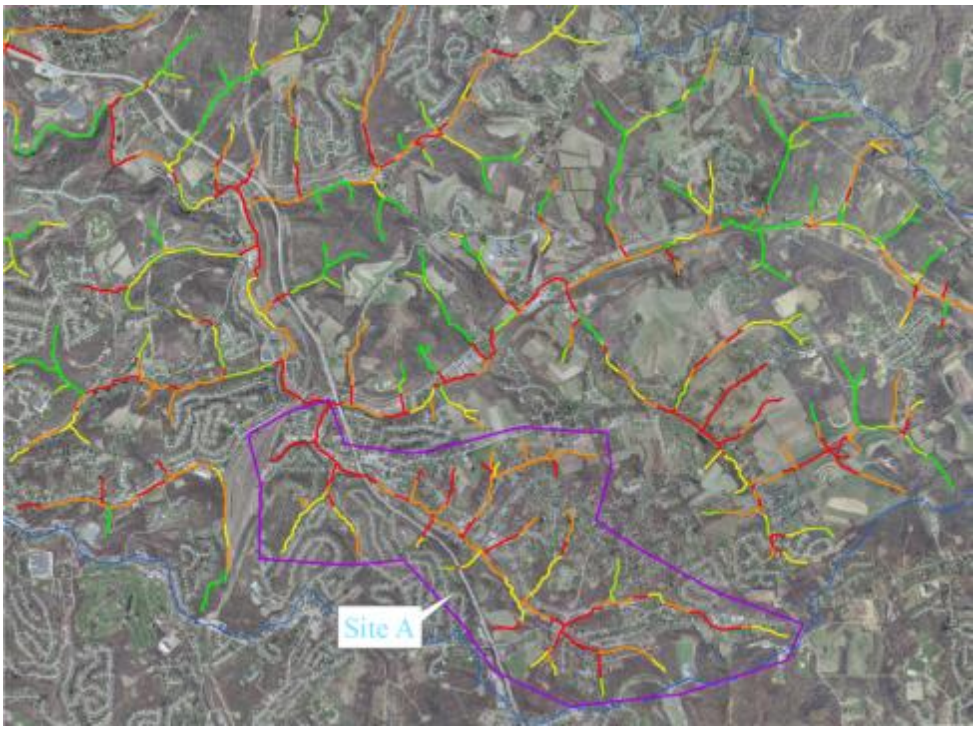


Figure 22: Intensive Plan Site B Overview



Figure 23: Riparian Zone Site A Overview



Acknowledgements

I would like to thank Professor Darby for all of her help and guidance throughout this project. You made this process so much more manageable and less stressful. I would also like to thank Chris Shaffer for providing me with the GIS knowledge that made this project possible.

References

Arnold Jr, C. L., & Gibbons, C. J. (1996). Impervious surface coverage: the emergence of a key environmental indicator. Journal of the American Planning Association, 62(2), 243–258.

Balingit, M. (2013, Feb 2). Fatal flooding in 2011 on Washington Boulevard brings suit against many. *Pittsburgh Post Gazette*. Retrieved from http://www.post-gazette.com/stories/local/neighborhoods-city/fatal-flooding-in-2011-on-washington-boulevard-brings-suit-against-many-673103/

Bilsborrow, R. E.*Migration, urbanization, and development: New directions and issues* [New York] : United Nations Population Fund ; c1998.

Black, P. E. (1996). *Watershed hydrology, second edition* Lewis Publishers, Inc.

Bliss, Daniel. (2004). Stormwater Runoff Mitigation and Water Quality Improvements Through the Use of a Green Roof in Pittsburgh, Pa. Master's Thesis, School of Engineering, University of Pittsburgh.

Booth, D. B., & Leavitt, J. (1999). Field evaluation of permeable pavement systems for improved stormwater management *Journal of the American Planning Association, 65*(3), 314-325. doi:10.1080/01944369908976060

Brattebo, B. O., & Booth, D. B. (2003). Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research, 37*(18), 4369-4376. doi: 10.1016/S0043-1354(03)00410-X

Bryan, E.H. (1972). Quality of storm water drainage from urban land. *Water Resources Bulletin*. vol. 8, no. 3, pp. 578-588.

Butler, S. US Department of Agriculture, (2005). Economics and survival of hand planted riparian forest buffers. Retrieved from National Resources Conservation Service website: ftp://ftp-fc.sc.egov.usda.gov/Economics/tools/Forest/EconSurvivalHandPlantedBuffers.pdf

Dengsheng, L., & Qihao, W. (2006). Use of impervious surface in urban land-use classification. Remote Sensing of Environment , (102), 146-160. Retrieved from http://isu.indstate.edu/qweng/RSE06.pdf

Dietz, M. E., & Clausen, J. C. (2005). A field evaluation of rain garden flow and pollutant treatment *Water, Air, and Soil Pollution, 167*(1-4), 123-138. doi:10.1007/s11270-005-8266-8

Environmental Protection Agency. (1993a). Guidance Specifying Management Measures for Sources of Nonpoint Source Pollution in Coastal Waters United States Environmental Protection Agency #840-B-92-002. Washington, DC: USEPA Office of Water.

Environmental Protection Agency, Office of Water. (2006). Bioretention (rain gardens). Retrieved from website: http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=72

Environmental Protection Agency, Office of Water. (2006). Dry detention ponds. Retrieved from website: http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=67

Environmental Protection Agency, Office of Water. (2006). Green roofs. Retrieved from website: http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=114

Environmental Protection Agency, Missouri Department of Natural Resources. (2013). Water quality-stormwater management. Retrieved from website: http://oa.mo.gov/fmdc/dc/fmdc_dip/10 Water Quality/fg05_07_stormwaterman.pdf

Ferguson, B. (2005). Why make pavements porous? CRC Press. doi:doi:10.1201/9781420038439.ch1

Gaffield, S. et al. (2003). Public health effects of inadequately managed stormwater runoff. American Journal of Public Health, 93(9), 1527-1533. Retrieved from http://ajph.aphapublications.org/doi/pdf/10.2105/AJPH.93.9.1527

Graham, P., and M. Kim. (2003). Evaluating the stormwater management benefits of green roofs through water balance modeling. p. 390-398. In Proc. of 1st North American Green Roof Conf.: Greening Rooftops for Sustainable Communities, Chicago. 29-30 May 2003. The Cardinal Group, Toronto.

Hager, M. C. (2003). Lot-level approaches to stormwater management are gaining ground. *Stormwater. January/February*.

Hogan, D. M., & Walbridge, M. R. (2007). Best management practices for nutrient and sediment retention in urban stormwater runoff. *Journal of Environmental Quality, 36*(2), 386-95.

Hopey, D. (2012, July 19). Federal grant to help Pittsburgh curb stormwater runoff. *Pittsburgh Post Gazette*. Retrieved from http://www.post-gazette.com/stories/news/environment/federal-grant-to-help-pittsburgh-curb-stormwater-runoff-645425/

Lazaro, T. R. (1990). *Urban hydrology: A multidisciplinary perspective* . Lancaster: Technomic Pub. Co.

Lee, J. H., & Bang, K. W. (2000). Characterization of urban stormwater runoff. Water Research, 34(6), 1773–1780.

Merz, B. et al. (2010). Assessment of economic flood damage. Natural Hazards and Earth System Sciences, (10), 1697– 1724. Retrieved from http://www.nat-hazards-earth-syst-sci.net/10/1697/2010/nhess-10-1697-2010.pdf

Monterusso, M.A., D.B. Rowe, C.L. Rugh, and D.K. Russell. (2004). Runoff water quantity and quality from green roof systems. *Acta Hortic*. 639:369-376.

Newkirk, R. T. (2000). Reducing downstream storm water impacts using design stage modeling in urban development. *Environments, 28*(1), 65-74.

Pagotto, C., Legret, M., & Le Cloirec, P. (2000). Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement. *Water Research, 34*(18), 4446-4454. doi: 10.1016/S0043-1354(00)00221-9

Pitt, R. et al. (1995). Urban Stormwater Toxic Pollutants: Assessment, Sources, and Treatability. Water Environment Research , Vol. 67, No. 3 (May - Jun., 1995), pp. 260-275.

Riparian buffers. Informally published manuscript, Stream Notes, North Caroline State University, Retrieved from http://www.bae.ncsu.edu/programs/extension/wqg/sri/riparian5.pdf

Sayre, J.M., Devinny, J.S., Wilson, J.P., (2006). Best Management Practices (BMP) for the Treatment of Stormwater Runoff. University of Southern California GIS Research Laboratory and Center for Sustainable Cities, Los Angeles, California.

Scholz, M., & Grabowiecki, P. (2007). Review of permeable pavement systems. Building and Environment, 42(11), 3830–3836. http://www.sciencedirect.com/science/article/pii/S0360132306004227.

Tsihrintzis, V. A., & Hamid, R. (1997). Water Resources Management, 11(2), 136-164. doi:10.1023/A:1007903817943

VanWoert, N. D., D Bradley Rowe, Andresen, J. A., Rugh, C. L., & et al. (2005). Green roof stormwater retention: Effects of roof surface, slope, and media depth. *Journal of Environmental Quality, 34*(3), 1036-44.

Walker, G., & Burningham, K. (2011). Flood risk, vulnerability and environmental justice: Evidence and evaluation of inequality in a uk context. Critical Social Policy, 21(2), 216-240. doi: 10.1177/0261018310396149